

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.					
1. REPORT DATE (DD-MM-YYYY) 17-06-2010		2. REPORT TYPE Technical Paper		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE Terahertz Rayleigh Scattering of Particles in Rocket Exhaust Plumes				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) A. O'Shea, T. Mulcahy, & H. Song (University of Colorado); A. Ketsdever (AFRL/RZSA)				5d. PROJECT NUMBER	
				5f. WORK UNIT NUMBER 50260542	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Air Force Research Laboratory (AFMC) AFRL/RZSA 10 E. Saturn Blvd. Edwards AFB CA 93524-7680				8. PERFORMING ORGANIZATION REPORT NUMBER AFRL-RZ-ED-TP-2010-287	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Research Laboratory (AFMC) AFRL/RZS 5 Pollux Drive Edwards AFB CA 93524-7048				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S NUMBER(S) AFRL-RZ-ED-TP-2010-287	
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited (PA #10283).					
13. SUPPLEMENTARY NOTES For presentation at the AIAA 10 th Joint Thermophysics and Heat Transfer Conference, Chicago, IL, 28 June – 1 July 2010.					
14. ABSTRACT Characterization of particles in solid rocket plumes has been difficult due to the lack of real-time measurement techniques. This research proposes a new technique using terahertz radiation and Rayleigh scattering on alumina particulates in the plume. Previous techniques have involved collecting particles on a probe or mesh. Others have used Mie scattering using lasers, but this technique is limited to firing the beam straight across the plume. Terahertz radiation wavelengths in relation to alumina particle sizes, 1 µm to 100 µm, align with the Rayleigh criterion, requiring that the wavelength of light be at least ten times greater than the radius of the particle. Rayleigh scattering would allow for changing the location of the detector and even co-locating it with the source. A theoretical analysis of a notional setup involving a terahertz source and aluminum oxide particles inside a rocket plume was performed. The results from this analysis showed that a 1 kW source coupled with approximately 75 dB gain antennas would be required to perform this experiment. Because terahertz sources above 100 W are currently unavailable, an experiment was setup using microwaves at 2.45 GHz and properly scaled aluminum balls of radii ranging from 2.38 mm to 9.52 mm. A magnetron power source was used to provide a power range of 1-100 Watts into a microwave anechoic chamber. These results showed the expected trends with respect to source power and ball radius versus scattered power.					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Dr. Andrew Ketsdever
Unclassified	Unclassified	Unclassified	SAR	13	19b. TELEPHONE NUMBER (include area code) N/A

Terahertz Rayleigh Scattering of Particles in Rocket Exhaust Plumes

A. O'Shea¹

Department of Mechanical and Aerospace Engineering
University of Colorado at Colorado Springs, Colorado Springs, CO 80921

T. Mulcahy² and H. Song³

Department of Electrical and Computer Engineering
University of Colorado at Colorado Springs, Colorado Springs, CO 80921

and

A. Ketsdever⁴

Air Force Research Laboratory, Propulsion Directorate, Edwards AFB, CA 93524

Characterization of particles in solid rocket plumes has been difficult due to the lack of real-time measurement techniques. This research proposes a new technique using terahertz radiation and Rayleigh scattering on alumina particulates in the plume. Previous techniques have involved collecting particles on a probe or mesh. Others have used Mie scattering using lasers, but this technique is limited to firing the beam straight across the plume. Terahertz radiation wavelengths in relation to alumina particle sizes, 1 μm to 100 μm , align with the Rayleigh criterion, requiring that the wavelength of light be at least ten times greater than the radius of the particle. Rayleigh scattering would allow for changing the location of the detector and even co-locating it with the source. A theoretical analysis of a notional setup involving a terahertz source and aluminum oxide particles inside a rocket plume was performed. The results from this analysis showed that a 1 kW source coupled with approximately 75 dB gain antennas would be required to perform this experiment. Because terahertz sources above 100 W are currently unavailable, an experiment was setup using microwaves at 2.45 GHz and properly scaled aluminum balls of radii ranging from 2.38 mm to 9.52 mm. A magnetron power source was used to provide a power range of 1-100 Watts into a microwave anechoic chamber. These results showed the expected trends with respect to source power and ball radius versus scattered power.

¹ Graduate Research Assistant, Department Name, Address/Mail Stop, AIAA Student Member.

² Graduate Research Assistant, Department Name, Address/Mail Stop.

³ Assistant Professor, Department Name, Address/Mail Stop.

⁴ Research Engineer, AIAA Associate Fellow.

Nomenclature

I_s	=	scattered intensity	ϕ	=	elevation angle
I_o	=	incident intensity	P_{det}	=	power to the detector
r	=	radius	η	=	scattering efficiency
n	=	index of refraction	θ	=	rotation angle
λ	=	wavelength of incident light	R	=	distance from transmitter to particle
d	=	distance from particle to detector	D_{dish}	=	diameter of the antenna dish
N	=	number density of particles	P_r	=	power received
v	=	observation volume	P_t	=	power transmitted
σ_{ss}	=	scattering cross-section	G_r	=	gain of the receiving antenna
$\frac{d\sigma_{ss}}{d\Omega}$	=	differential scattering cross-section	G_t	=	gain of the transmitting antenna
Ω	=	collection solid angle	r_{dish}	=	radius of the antenna dish
V	=	volume of the particle	f	=	frequency of light

I. Introduction

The terahertz region of the electromagnetic spectrum between 100 GHz and 10 THz (wavelength range from 3000 μm to 30 μm) occupies a large portion of the spectrum between the infrared and microwave bands. Compared to the relatively well-developed science and technology at microwave, optical and x-ray frequencies, developments in the terahertz band are limited and remain relatively unexplored¹. The shorter wavelengths at terahertz frequencies allow the use of smaller and lighter components, which is important in military and air-borne applications. In addition, compared to infrared and optical wavelengths, atmospheric attenuation in the terahertz region is relatively low².

The understanding of multiphase rocket exhaust plume flows is important to many scientific and engineering applications. Chemical combustion processes involve high temperature, multiphase flows from liquid fuel injectors in internal combustion engines to plume effluents at the exit plane of a rocket nozzle. The terahertz region of the electromagnetic spectrum may have a large impact on the general understanding of these two-phase flows for particle sizes between 1 μm and 100 μm . Rayleigh and Raman spectroscopy has been used to diagnose homogenous and heterogeneous cluster formation, condensation, and evaporation in a high-temperature gaseous flow environment. THz excitation sources bring about a new possibility to interrogate flows that otherwise could not be investigated with normal Rayleigh or Raman techniques because of the correlation between terahertz frequencies and the range of particle size with respect to the Rayleigh criterion.

This study seeks to characterize alumina particles in solid rocket plumes. Particles in rocket plumes are difficult to measure accurately. Some current methods involve collecting particles on a screen or sticking a probe into the plume itself³. While these methods have produced results they require a static setup and can be subject to contamination. This study will investigate the use of terahertz radiation and the principles of Rayleigh light scattering to accurately determine particle number density, size, and velocity. One may use Mie scattering with the particle sizes for solid rocket motors, but the setup would once again have to be static due to the general forward-scattered direction of Mie scattered light. Lasers have also been applied to hydrogen and oxygen rocket engines using laser and Rayleigh scattering⁴. The study wants to look at solid rocket motors which produce particles between 1 μm and 100 μm ⁵. For these size particles, terahertz provides wavelengths from 10 μm to 1 mm which are ideally suited to measure the particles in the plume with Rayleigh scattering. The setup is not restricted to a static fire and could be used in a real time launch configuration. The use of the Rayleigh criterion also removes the large complications surrounding Mie theory.

The applications of the study include plume particle characterization for different propellant compositions, which could lead to improvements in the efficiency as a function of different propellant mixtures. Also, this tool could be used to measure the efficiency and particle sizes in startup and shut down of solid rocket motors. This study develops a notional terahertz instrument with the capability transmitting to a rocket and measuring Rayleigh scattered light from alumina particles. Also, in order to test the feasibility of such an instrument, this study performs a scald experiment using microwaves at 2.45 GHz and a variety of input powers. The experiment measures the scattered light off of aluminum balls of various sizes.

II. Theory

A. Rayleigh Scattering

Rayleigh scattering is attributed to Sir John Rayleigh who is well known for describing the blue color of the sky. He concluded that the ratio of scattered light intensity to incident light intensity is proportional to the sixth power of the particle radius and inversely proportional to the distance from the particle squared and the fourth power of the wavelength of light. Rayleigh scattering is elastic scattering where the frequency of scattered light is equivalent to the frequency of the incident light. Fundamentally, Rayleigh scattering is an approximation of the overarching theory of Mie scattering which is also elastic in nature. However, there is one important limitation on Rayleigh scattering. The particle's radius must be at least ten times smaller than the wavelength of the incident light. If the particle is any larger the theory does not conform to the values obtained using Mie theory. An advantage of Rayleigh scattering over Mie scattering is the relative simplicity in calculating predicted scattered powers. Mie theory is a complicated process involving either several infinite sums of Legendre polynomials or multiple infinite sums of Bessel of several kinds and Hankel functions. Rayleigh theory simplifies the Mie theory equations into one simple ratio of scattered intensity (I_s) to incident intensity (I_o)⁶

$$\frac{I_s}{I_o} = \frac{16\pi^4 r^6 \left(\frac{n^2 - 1}{n^2 + 2} \right)^2}{\lambda^4 d^2} \quad 1$$

The scattered intensity represented in Eq. (1) is the total intensity of light scattered from the particle. If one wants to detect scattered light, only a portion of this light will end up at a given sensor. The solid angle of the sensor's collection aperture must be taken into account using the following equation.

$$I_s = \int_0^\Omega N \nu I_o \frac{d\sigma_{ss}}{d\Omega} \quad 2$$

This integral can be used to determine either the mean size of particles or the number density of particles with a certain size.

Another property of light scattering in the Rayleigh regime is the scattered intensity has an almost uniform dispersion. In the Mie regime the scattered intensity tends to be in the same direction as the incident light. This fact gives an experiment using the Rayleigh regime of scattered light more flexibility in set up because more light can be easily detected in a wide variety of sensor locations. Figure 1 illustrates the difference in scattering patterns between Mie and Rayleigh.

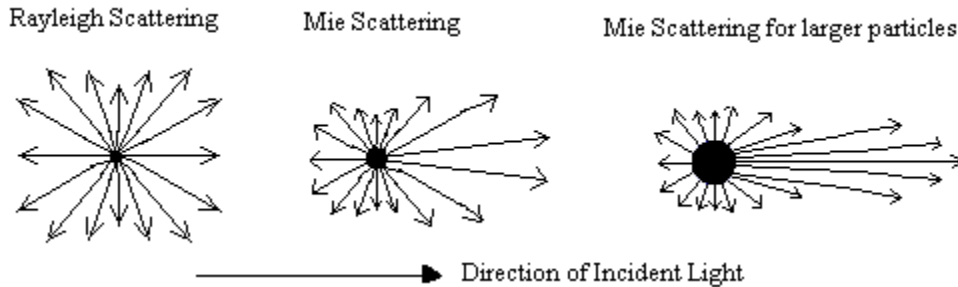


Figure 1. Depiction of elastic light scattering

B. Rayleigh Approach

The intensity of light scattered from a particle is a function of the incident intensity of light, particle radius, distance, and wavelength as shown in Eq. (1). Eq. (1) represents the total intensity of light scattered. In general it is not feasible to collect all of the scattered light. In fact only a small portion of this light can be measured through the collection aperture. In order to better analyze the situation, one can define a differential cross-section.

$$\frac{d\sigma_{ss}}{d\Omega} = \frac{9\pi^2 V^2}{\lambda^4} \left(\frac{n^2 - 1}{n^2 + 1} \right)^2 \sin^2 \phi \quad 3$$

From Miles, Lempert, and Forkey, the total collected power becomes the integral of the number of particles multiplied by the scattering differential cross-section, the incident intensity, and the scattering efficiency over the collection solid angle. Namely,

$$P_{det} = \eta I_I N v \int_{\Omega_1}^{\Omega_2} \frac{d\sigma_{ss}}{d\Omega} d\Omega \quad 4$$

The differential solid angle can be represented as

$$\delta\Omega = \sin(\phi) d\phi d\theta \quad 5$$

which when applied to the integral for detected power becomes

$$P_{det} = \eta I_I N v \int_{\theta_1}^{\theta_2} \int_{\phi_1}^{\phi_2} \frac{9\pi^2 V^2}{\lambda^4} \left(\frac{n^2 - 1}{n^2 + 2} \right)^2 \sin^3(\phi) d\phi d\theta \quad 6$$

Evaluating the integral in Eq. (6) for the power yields the equation

$$P_{det} = \eta I_I N v \frac{9\pi^2 V^2}{\lambda^4} \left(\frac{n^2 - 1}{n^2 + 2} \right)^2 \left(\frac{(\theta_1 - \theta_2)(\cos(3\phi_1) - \cos(3\phi_2) - \cos(9\phi_1) + \cos(9\phi_2))}{12} \right) \quad 7$$

In a particular experimental setup, certain values can be controlled and are known. The values for incident intensity, wavelength, refractive index, and collection angle are known. Also the experiment will yield a value for the scattered power. Unfortunately, this leaves two unknown values and only one equation. Those values are particle number density and particle radius. In past experiments utilizing Rayleigh scattering the number density was either known or reasonably approximated. For example, Zhang et al⁷ measured the size and number density of glycogen molecules. However, in their experiment, the size of glycogen was relatively well known as well as the concentrations of the solutions they used which gives a relation to number density. Also, An-Le et al⁸ measured the size of Argon clusters using Rayleigh scattering; however, they were able to relate both size and number to their reservoir pressure. Unfortunately, these values are not generally known for alumina particles in solid rocket plumes. There have been studies conducted to determine particle size based on the propellant characteristics. O. B. Kovalev⁹ discussed the formation of aluminum oxide in rocket plume and generated an analytical prediction method for the size of the particles. However, the particle number density and size in a typical rocket plume will be generally unknown. Therefore, this technique may be restricted to measuring the product of NV^2 unless other methods can be developed in the future. One such method may involve sweeping frequencies. This would be beneficial because as the frequency increases, the larger particles enter the Mie regime and the change in scattered return can be measured and analyzed to calculate a number density for a certain particle radius. The process could be repeated to account for all particle sizes of interest. Also, using interferometry could lead to calculating the velocity of the particles¹⁰.

III. Application

A. Terahertz Predictions

Several predictions can be made for the planned terahertz instrument. These predictions include finding the expected scattered power for a variety of particles sizes, number of particles, incident powers, and input frequencies. Figure 2 shows the expected relation between total scattered power and incident power for a 10 μm radius aluminum-oxide particle and a frequency of 300 GHz. There is a well known linear relation between incident power and scattered power, and this plot clearly shows that a higher incident power is beneficial for measuring the scattered power. Figure 3 depicts the relation between the number density of particles in a 1 m^3 region of interrogation and scattered power assuming no inter-particle interactions for a fixed output power of 1 kW, and a frequency of 300 GHz, and a 10 μm particle size. The relation is also linear for number of scattering particles and scattered power which highlights the benefit of measuring a large number of particles for a stronger signal. Figure 4 shows the relation between input frequency and scattered power with multiple particle radii. The input power is fixed at 1 kW, and the single particle size is 1 μm . Here the relation to frequency is inversely proportional to the fourth power of the wavelength. The plot shows that in order to maintain high scattered power, one must try to optimize the frequency for the particle size meaning that the wavelength is ten times the particle radius.

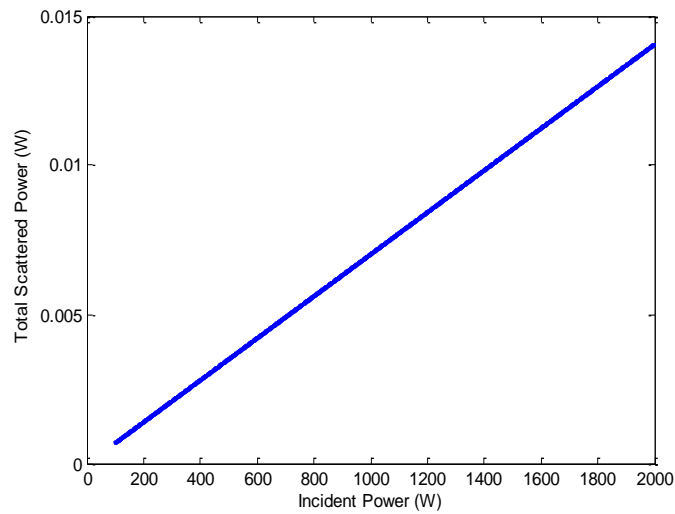


Figure 2. Relation between incident power and total scattered power

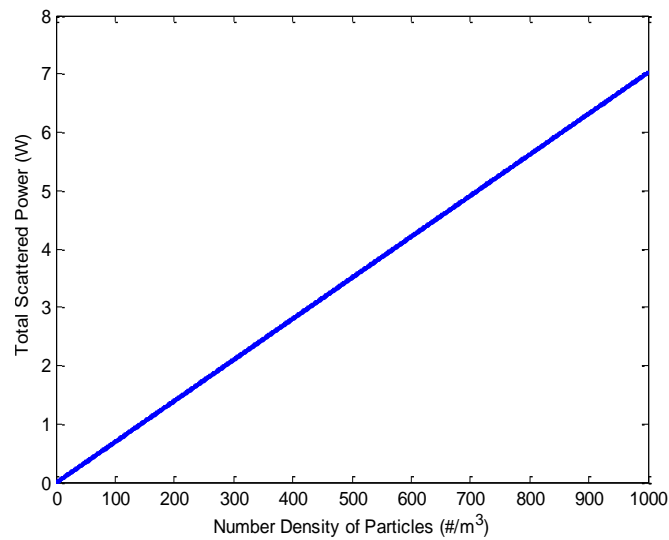


Figure 3. Relation between number density and total scattered power

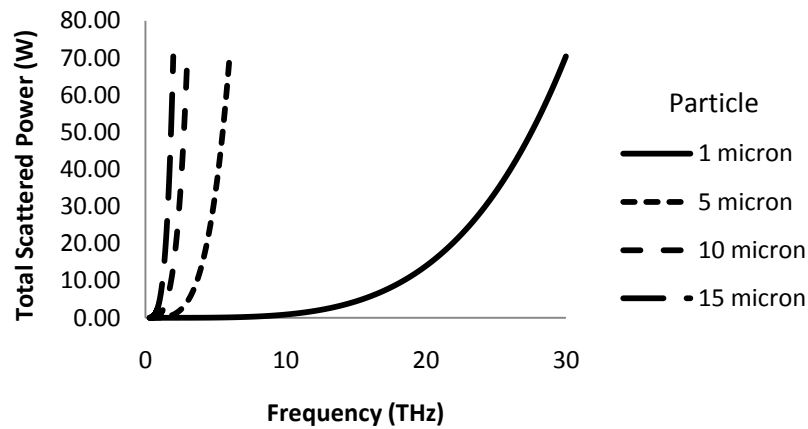


Figure 4. Relation between frequency, particle radius, and total scattered power

B. Design of a Notional Terahertz Instrument

For an actual experimental setup involving terahertz radiation and Rayleigh scattering, one must consider the challenges of transmitting across large distances while scattering off particles inside the rocket plume. For these predictions of the required power for a source, certain assumptions were made. For Rayleigh to apply, the wavelength was ten times greater than the particle radius. Also, the criteria for far-field transmission were used as defined by Stutzman¹¹.

$$\begin{aligned} R &\gg \lambda \\ R &\gg D_{dish} \\ R &> \frac{2D_{dish}^2}{\lambda} \end{aligned} \quad 8$$

After satisfying these criteria, the Friis transmission formula¹² was used to calculate the ratio between the power at the scattering particle and the power transmitted.

$$\frac{P_p}{P_t} = G_t \left(\frac{\lambda}{4\pi R} \right)^2 \quad 9$$

The notional setup uses parabolic antennas to transmit and receive. The gains for the antennas are based on frequency and the radius of the dish and can be calculated with the following equation¹³.

$$G = 17.8 + 20 \log D_{dish} + 20 \log f \quad 10$$

The power transmitted to the particle is used to calculate the incident intensity by dividing the power by the cross-sectional area of the particle. The incident intensity is used in Eq. (7). With this setup, the integral bounds of the scattering cross-section can be defined in terms of the distance to the particle and the radius of the antenna dish; namely,

$$\phi_1 = \frac{\pi}{2} - \tan^{-1} \left(\frac{r_{dish}}{R} \right) \quad \phi_2 = \frac{\pi}{2} + \tan^{-1} \left(\frac{r_{dish}}{R} \right) \quad 11$$

$$\theta_1 = \frac{\pi}{4} - \tan^{-1} \left(\frac{r_{dish}}{R} \right) \quad \theta_2 = \frac{\pi}{4} + \tan^{-1} \left(\frac{r_{dish}}{R} \right) \quad 12$$

The final ratio between received power and transmitted power can be written as

$$\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi R} \right)^2 \eta I_I N \nu \frac{9\pi^2 V^2}{\lambda^4} \left(\frac{n^2 - 1}{n^2 + 2} \right)^2 \int_{\theta_1}^{\theta_2} \int_{\phi_1}^{\phi_2} \sin^3(\phi) d\phi d\theta \quad 13$$

Figure 5 shows the effects of distance and antenna size on the power ratio Eq. (13) for a single 100 micron scattering particle. The graphs show that while a large antenna provides more gain, the effects of increased distance, due to the far-field restrictions, are a greater detriment to the power ratio. Overall, the relation is inversely proportional to the fourth power of the range. Figure 6 depicts the relation between antenna radius and the power ratio assuming that the range is at the minimum distance while still satisfying the far-field criteria. Again it shows the inverse proportionality to the fourth power of the distance to the particle.

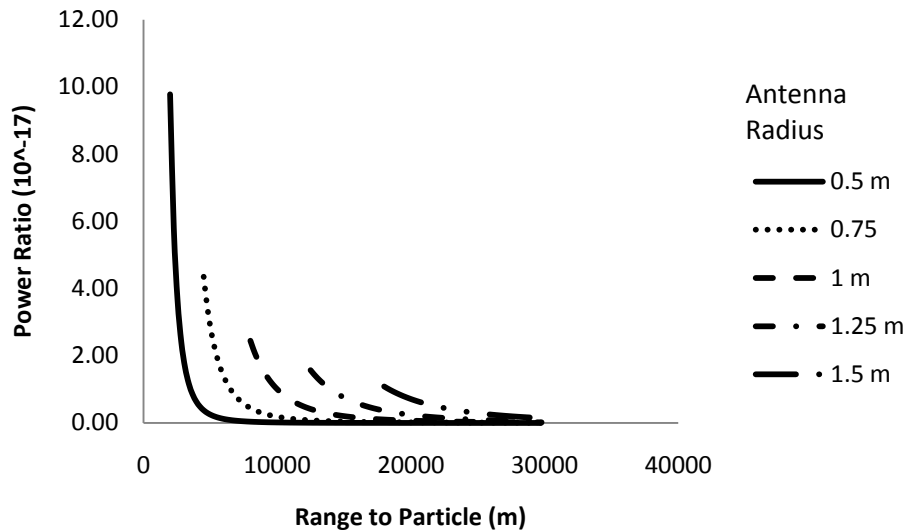


Figure 5. Relation between range to particle and power ratio with multiple antenna radii

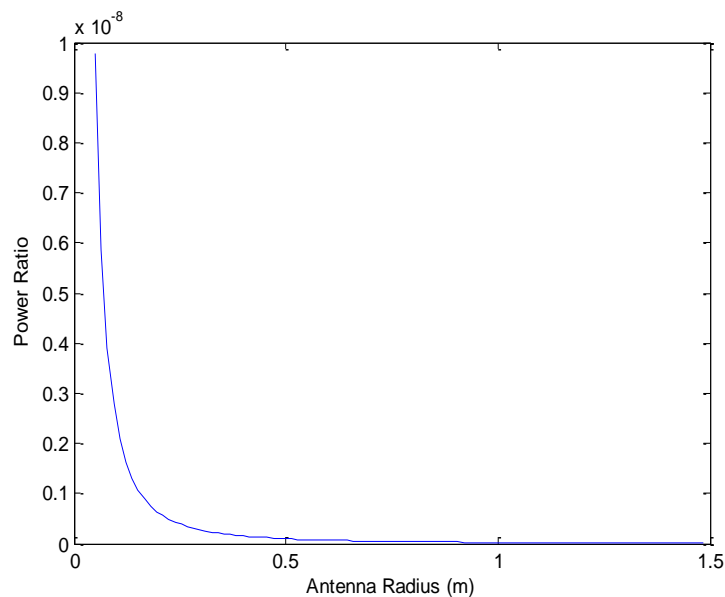


Figure 6. Relation between antenna radius and power ratio assuming minimum range to particle

From Figures 5 and 6, one can see that for a notional terahertz instrument a high power source is required with high gain antennas. These figure show that the biggest detriment to scattered power is distance. Also, the power ratio for a single particle is very small. However, the number density for solid rocket plumes can be approximated to be on the order of 10^8 to 10^{10} particles per cubic meter¹⁴. This number density would allow a 1 kW source using 1.5 m radius antennas to measure scattered powers in the μW range at 20 km. Figure 7 depicts what the notional setup may look like.

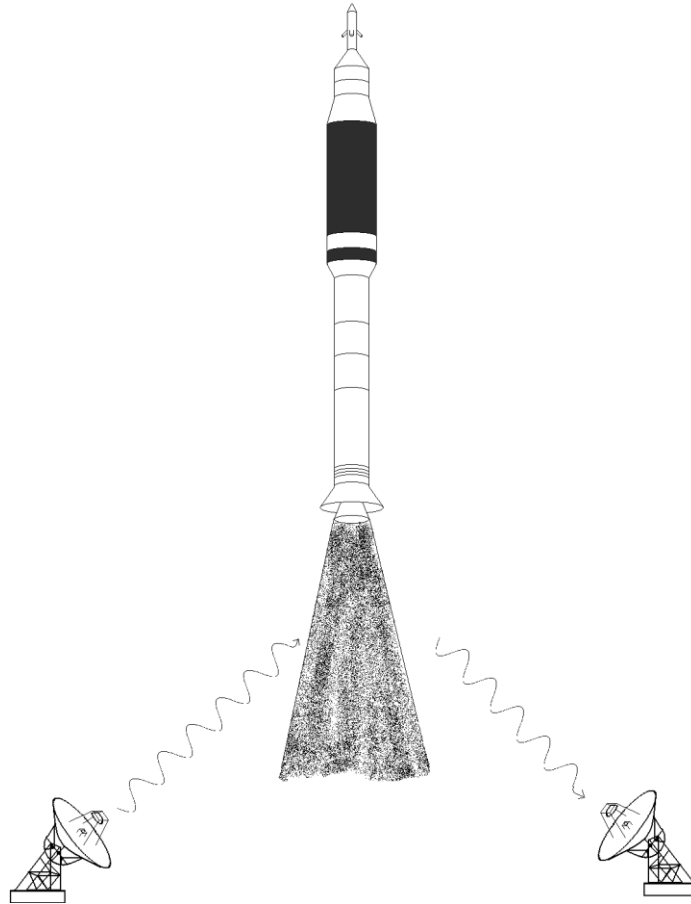


Figure 7. Notional Terahertz Instrument

IV. Experiment

A. Experimental Setup

The Electrical and Computer Engineering Department at the University of Colorado at Colorado Springs is currently developing the terahertz source that will eventually be used in this project. Therefore, this experiment is a scaled version of the proposed terahertz instrument. The current experiment uses microwaves and larger particles in order to demonstrate Rayleigh scattering. The frequency used in the experiment is 2.45 GHz which corresponds to a wavelength of 0.1224 m. Thus, the particles used in testing must have a radius smaller than 1.224 cm in order to satisfy the Rayleigh criterion.

The setup consisted of a power source transmitted through a horn antenna. The transmitted power scattered off a particle, and the scattered energy was collected in another horn antenna. The microwave power was provided by an Opthos MPG-4 which used a magnetron source. The transmitted power was run through a HP 777D Dual Directional Coupler in order to measure the transmitted and reflected power. The forward power from the Opthos source was measured using a HP 8481A power sensor connected to an Agilent E4419B EPM Series Power Meter. The measured data was recorded using Lab View. Microwaves were passed through coaxial cables and emitted into an anechoic chamber from a WR284 16.5 dB standard gain horn. The microwaves traveled approximately 2.89 m to the ball satisfying the far-field requirement. The balls used were made out of 2017-T4 aluminum and balls range in size from 2.38 mm radius to 9.52 mm. They are supported with 6.35 mm outer diameter 4 mm inner diameter quartz tubes. Figure 8 shows the geometry for the setup of the horns and the ball from a top view.

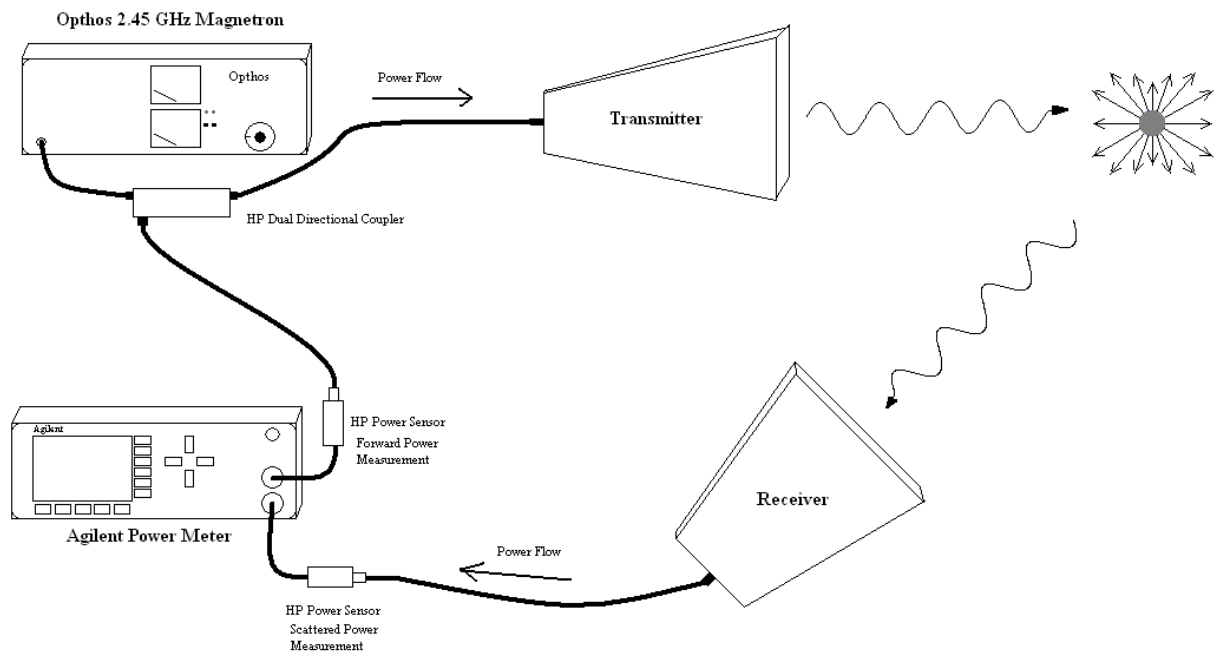


Figure 8. Illustration of the experimental setup

The scattered microwaves were collected in another WR284 16.5 dB standard gain horn. The received power was again passed through coaxial cables out the anechoic chamber to another HP 8481A Power Sensor which was also connected to the Agilent E4419B EPM Series Power Meter. The concept of using microwave horns as both the transmitting and receiving antennas is consistent with Zhang, Shneider, and Miles¹⁵ who used a similar setup to measure Rayleigh scattering using microwaves from resonance-enhanced multiphoton ionization in argon. They used a 10 mW source at a frequency of 12.6 GHz and collected the scattering in a microwave homodyne receiving system. Shneider and Miles¹⁶ also performed microwave Rayleigh scattering. Using frequencies of 3 and 6 GHz, they performed plasma diagnostics by treating the plasma as a point dipole source and collecting the Rayleigh scattered light off of the plasma.

The experiment was repeated for each of the ball sizes. The input power from the Opthos source ranged from approximately 50 Watts to 80 Watts. The experiment was also run with just the quartz rod and no ball in the chamber. The collected power from the “no ball” run was subtracted from each of the recorded tests with a ball in the chamber as a zero signal reference. The difference is taken as the scattered power and is used in comparison with the other tests. Four data points were taken which represent the average of multiple individual tests. The four points correspond to input powers that are approximately 50 Watts to 80 Watts with a 10 Watt step.

B. Results

For this experiment, the antennas operated in the far-field. Thus, accurate predictions of the expected received power could be made and compared with the experimental data. Therefore, the goal of the experiment was to look for the appropriate trends in the data and check for accuracy against the predictions.

The first task was to look for the linear trend between increasing source power and increasing received scattered power as well as good correlation with the predicted numbers. The following figures display the results from tests with three different ball sizes: 9.52 mm, 4.76 mm, 2.38 mm. The error bars are the standard deviations 13 individual tests. Figure 9 shows the results from test with the 9.52 mm aluminum ball. It shows the linear relation as well as a maximum percent difference between the predicted and experimental data of 9.1%. Figure 10 shows the relation between source and scattered power for the 4.76 mm aluminum ball. It also has a linear relation, but the maximum percent difference grew to 219%. The large error bars, especially with the smaller ball size, are a cause for concern. There are some sources of error that need be addressed. With the smaller size balls, the scattered power is close to the resolution range for the power sensor because the source does not generate enough power. There is increased noise in those signals which would lead to high standard deviations and high percent errors between the measured and predicted. Finally, small inconsistencies in the transmitted power would lead to slight differences in scattered

power. To mitigate these errors, a more sensitive setup will be used in the future including a 2 kW microwave power source which will allow for more accurate measurements.

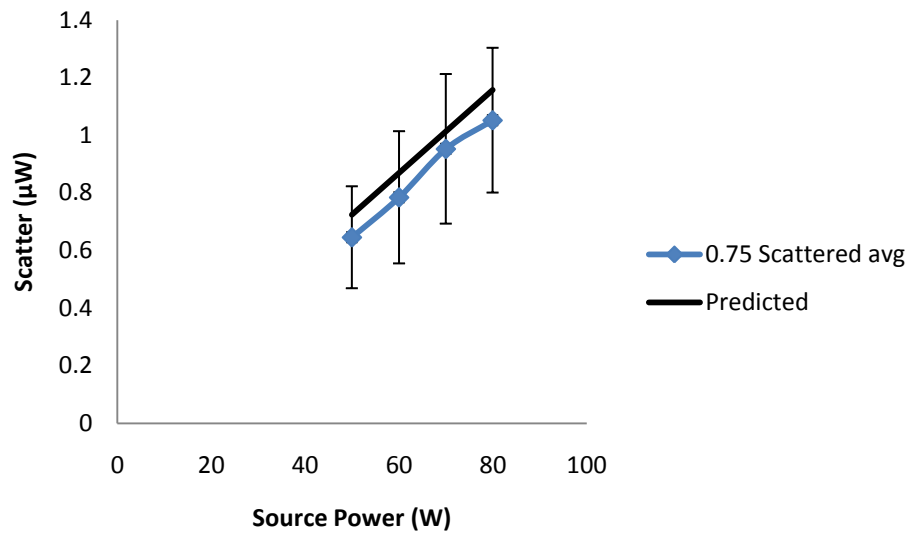


Figure 9. Scattered power as a function of source power for results and predictions for 9.52 mm ball

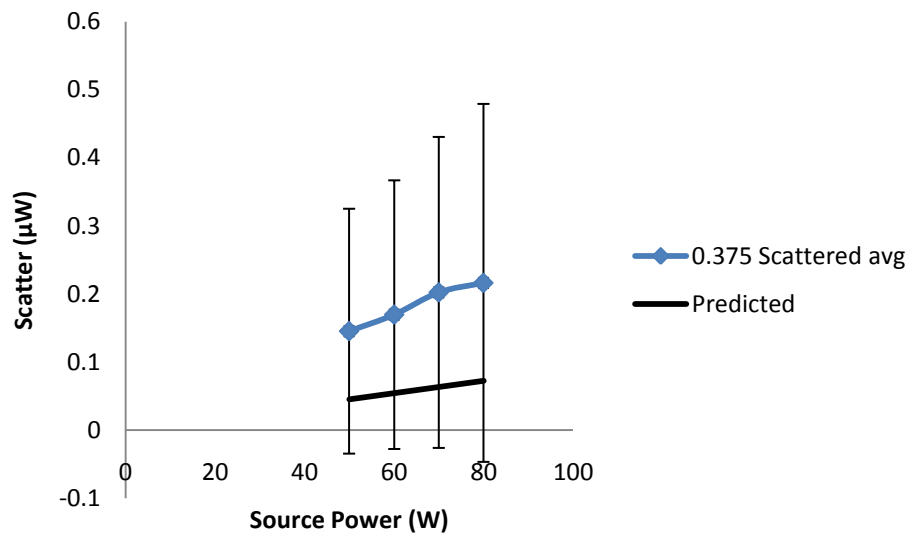


Figure 10. Scattered power as a function of source power for results and predictions for 4.76 mm ball

After establishing mostly linear relations between the source and scattered powers, the data was compared to check for the sixth order polynomial relation between increasing ball sizes. Figure 11 illustrates the results of increasing ball size at 70 Watts. In this plot the sixth order polynomial trends are similar with a percent difference of 5.7% for the largest ball size.

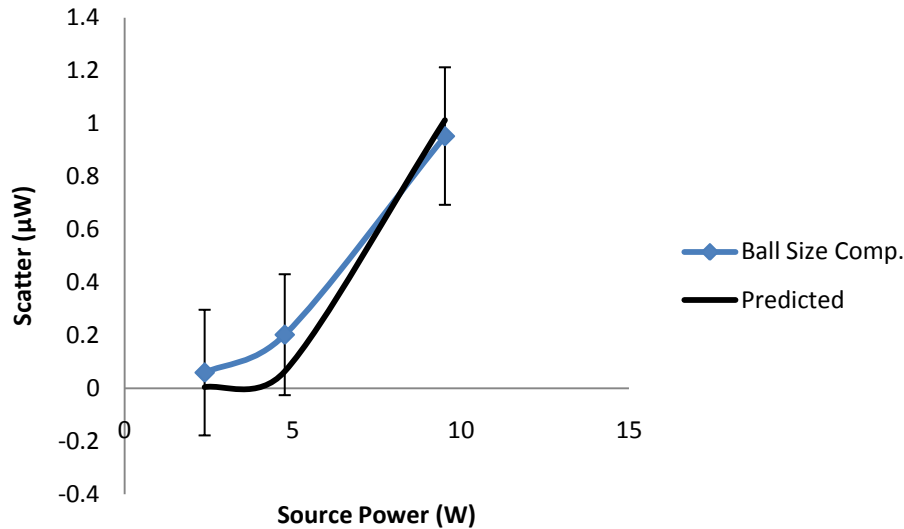


Figure 11. Scattered power as a function of ball radius for results and predictions at 60 W source power

The trends generated from the data are to be expected. The linear relation between increasing transmitted power and received power is to be expected. Also, the sixth power polynomial fit for the increasing ball radius is also to be expected based on Eq. (13). Therefore, the experiment has produced the appropriate trends.

V. Conclusion

In short, Rayleigh scattering coupled with Terahertz radiation may lead to a new characterization technique for particles in solid rocket plumes. This analysis would serve as a measure of efficiency of solid rocket motors. It could be used as a diagnostic for the performance of new compositions and the efficiency of start-up and shut-down procedures. However, from the requirements on such a system would be large in both the power from the source and the gain of the antennas. The notional setup would likely have a 1 kW terahertz source that transmits through parabolic antennas with a 1.5 m radius. This instrument would be able to measure scattered power in the μW range depending on the number density from about 20 km away. To test the feasibility of the system, a scaled experiment was conducted using microwaves at 2.45 GHz and aluminum balls. The results from this experiment showed the expected trends related source power to scattered power and ball radius to scattered power. These results also correlated relatively well with the predicted results. Despite the large percent errors between the predicted and the differences in the numbers can be accounted as noise and will be mitigated with a new setup and higher transmitted power. The only drawback is the size of the error bars which is a cause for minor concern. There are some sources of error that may account for the large standard deviations which will need to be addressed. Future research will improve upon the experimental setup and resolve many of the issues surrounding error and prediction. Despite the setbacks for smaller ball sizes the 9.52 mm ball size was in good agreement with the theory. Thus, with a ball closely matched to its maximum Rayleigh wavelength accurate measurements do not necessarily require a high amount of transmitted power. The same concept should hold true for transmitting terahertz radiation into a rocket plume. Frequency matching will be very beneficial to taking Rayleigh measurements.

Acknowledgements

This work was supported by the NISSSC, CSS, and EAS at UCCS. The authors wish to thank Dr. Scott Trimboli, Dr. Dan Dandapani, and Mr. Keagen Cothern.

References

- ¹X-C. Zhang, "Terahertz imaging: horizons and hurdles," *Phys. Med. Biol.* 47, 2002.
- ²K. J. Kim *et. al*, "Design considerations for a megawatt CW gyrotron," *Int. J. Electron.*, vol. 51, pp. 427 445, 1981.

- ³Sambamurthi, Jay K. "Al₂O₃ Collection and Sizing from Solid Rocket Motor Plumes." *J. of Propulsion and Power*. Vol. 12, No. 3 May-June 1996.
- ⁴Seasholtz, R. G., F. J. Zupanc, and S. J. Schneider. "Spectrally Resolved Rayleigh Scattering Diagnostic for Hydrogen-Oxygen Rocket Plume Studies." *Journal of Propulsion and Power*. Vol. 8, No. 5. Sept.-Oct. 1992.
- ⁵Simmons, Frederick S. *Rocket Exhaust Plume Phenomenology*. El Segundo, California: The Aerospace Press, 2000.
- ⁶Miles, Richard B., Walter R. Lempert, Joseph N. Forkey. "Laser Rayleigh Scattering." 2001 Meas. Sci. Technol. 12 R33.
- ⁷Zhang, Shu Zhen et al. "Determination of glycogen by Rayleigh light scattering." *Analytica Chimica Acta*. Vol. 431. 2001.
- ⁸An-Le, Lei et al. "Size Determination of Argon Clusters from a Rayleigh Scattering Experiment." *Chinese Physical Letters*. Vol. 17, No. 9 2000.
- ⁹Kovalev O. B. "Prediction of the Size of Aluminum-Oxide Particles in Exhaust Plumes of Solid Rocket Motors." *Combustion, Explosion, and Shock Waves*. Vol. 38, No. 5. 2002.
- ¹⁰Farmer, W. M. "Measurement of Particle Size, Number Density, and Velocity Using a Laser Interferometer." *Applied Optics*. Vol. 11, No. 11. November 1972.
- ¹¹Stutzman, Warren L. and Gary A. Thiele. *Antenna Theory and Design*. New York: John Wiley and Sons, 1981.
- ¹²Ulaby, Fawwaz T. *Fundamentals of Applied Electromagnetics*. Upper Saddle River, NJ: Pearson Prentice Hall, 2007.
- ¹³Larson, Wiley J. and James R. Wertz ed. *Space Mission Analysis and Design*. El Segundo, California: Microcosm Press, 1999.
- Cornella, Barry et al. "Thrust Augmentation of Solid Rocket Motors Using Beamed Microwave Energy." *J. Propulsion and Power*.
- ¹⁵Zhang, Zhili, Mikhail N. Shneider, and Richard B. Miles. "Coherent Microwave Rayleigh Scattering from Resonance-Enhanced Multiphoton Ionization in Argon." *Physical Review Letters*. Vol. 98, 265005. 2007.
- ¹⁶Shneider M. N. and R. B. Miles. "Microwave diagnostics of small plasma objects." *J. of Applied Physics*. **98**. 2005.